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Recent developments and prospects for algae-based fuels in the US

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ABSTRACT

In recent years, algae-based fuels have received a growing interest of the industry sector and the US Government as a sustainable and renewable energy source. Algae constitute a unique feedstock as they contain high levels of both lipids and sugars and, thus, can be used for both biodiesel and ethanol production successively, in a two-stage process. In addition, the production of algae-based fuels shows a low environmental footprint and high energy efficiency. Algae can produce between 10 and 100 times more oil per acre as compared with traditional oil crops (e.g., oil palm) and can also grow 20–30 times faster than food crops. The production of algae does not compete with traditional crops for fresh water, high quality soil or fertilizers and, if cultivated off-shore, algae production does not require land resources at all. Furthermore, algae-based fuel is carbon-neutral, as algae assimilate similar amounts of CO_2 for its growth as is released upon fuel combustion. From the policy perspective, algae-based fuels can provide a buffer for mitigating the food/feed vs. fuel problem in the long-term.

The paper analyzes and discusses very recent developments in the algae R&D from the economic, environmental and policy perspective. It presents ways for solving the economic impediments as well as prospects for the commercialization of the algae technology in the near future. It covers multiple scientific and industry-related research and experimental studies to provide a comprehensive picture of the trends and patterns in the field.

Contents

1. Opportunities for algae technology on the biofuels market

In 2010, the US was importing two-thirds of its petroleum, 60% of which being used for producing transportation fuels [1]. Growing demand for oil, limited oil reserves, oil price volatilities, and greenhouse gas (GHG) emissions from gasoline combustion are only a few aspects triggering policy interests in national biofuels production. In recent years, conventional biofuels from food crops (e.g., corn, soybean, canola) have turned out to create a difficult tradeoffs market condition between food/feed and fuel production, especially recently in the face of unexpected weather events and the 2011–2012 drought. Thus, advanced biofuels from cellulosic plant material (e.g., switchgrass, miscanthus) or oil plants (jatropha, oil palm) have become promising feedstocks in terms of their low environmental footprint, high energy efficiency and positive social impacts. Despite those positive indicators,

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cellulosic biofuels might not reach the production/consumption levels as expected (compare: [2]). The reason for this includes many technological and production uncertainties, but most importantly, the new and promising technologies emerging on the biofuels market. One of them is algae-based fuel.

In most research studies on algae-based fuels, the term 'algae' is used to refer to *microalgae* that are currently the main feedstock for biofuels production. Microalgae are unicellular organisms with less than 0.016 in. in diameter. They also comprise *cyanobacteria* ('blue-green algae') even though they combine characteristics of bacteria and algae. Both have the capacity of photosynthesis and binding CO_2 (carbon dioxide) for their growth and reproduction. Thus, they bear a very high potential for a positive environmental footprint. Despite the fact that cyanobacteria can be neurotoxic, cause serious health problems in humans, disturb the ecosystem balance in lakes and ponds and negatively impact biodiversity, it can also be used as a valuable and efficient feedstock for biofuels production. Another group of algae is *macroalgae* (seaweed) that was not very successful in experimental biofuels production to date with near-shore cultivation projects in China, Japan and Chile. The limitations for using macroalgae for large scale biofuels production, as compared to microalgae, are: a more complex structure, slower growth rate and lower oil content [3,4].

This paper is focused on microalgae fuel and the potential contribution of this algae group to advanced biofuels market in the near future.

The algae-based fuel technology can be called a market innovation as it offers a unique opportunity to produce both biodiesel and ethanol successively in a two-step process. This is possible since algae contain both oil (in algae cells) and sugars (starch – the storage component and cellulose – the cell wall component). None of the other biofuels technologies currently available on the market offers similar advantages.

The most efficient algae strains for ethanol production are *Sargassum*, *Glacilaria*, *Prymnesium parvum and Euglena gracilis* as they have the highest carbohydrate content among algal strains. After extracting lipids from algae cells, the left-over cake composed of carbohydrates and proteins can be converted into sugars and finally ethanol in the fermentation process. Fermentation of the algae extract releases CO_2 which can again be used to grow more algae [5].

2. Possibilities for and limitations of the algae technology

Algae deliver the highest lipid amount among all biofuels feedstocks available on the market nowadays and have a very fast growth rate, assuming favorable weather conditions. Oil yields from certain algae strains can be 300 times (and more) higher than from corn, 130 times higher than from soybeans, 30 times higher than from jatropha, and approximately 10 times higher than oil palm per ha of land on an annual basis (see Table 1). In addition, algae can grow 20–30 times faster than food crops and it has a harvesting cycle of 1–10 days, which allows for several harvests in a very short time frame [6,7]. The efficiency of lipid production by algae strains depends mainly on the temperature and sun exposure. According to Sandias National Laboratories, the most favorable growing conditions for algae are in regions with annual average sun hours ≥ 2800, annual average daily temperature $\geq 55\ ^{\circ}F$ and annual average freeze-free days ≥ 200 [1]. Accordingly, Quinn et al. [8] estimated the highest annual lipid productivity from algae cultivated in photobioreactors to be in Hawaii (22–27 m^3/ha), Southern California and Arizona (20–24 m^3/ha), New Mexico and Texas (18–22 m^3/ha). However, it needs to be mentioned that various species of microalgae are capable of growing under a wide range of temperatures. Thus, depending on the algae strains, different regions might provide optimal growing conditions.

The process of producing algae-based fuels (ethanol and biodiesel) and deriving algae-based products is complex and occurs in several stages (Fig. 1). Depending on the algae strain, applied technology, constituents and biological conversion processes, the cost of the final product (fuel and co-products) may differ.

According to Oligea [5], producing ethanol from algae is not problematic in terms of the technological process. Rather, the algal feedstock is competitive in terms of the final product. As other products derived from microalgae and macroalgae (e.g., carrageenan, agar) are highly priced as compared to the low-price value of algae-based fuels (Table 2), the economic aspects and profit

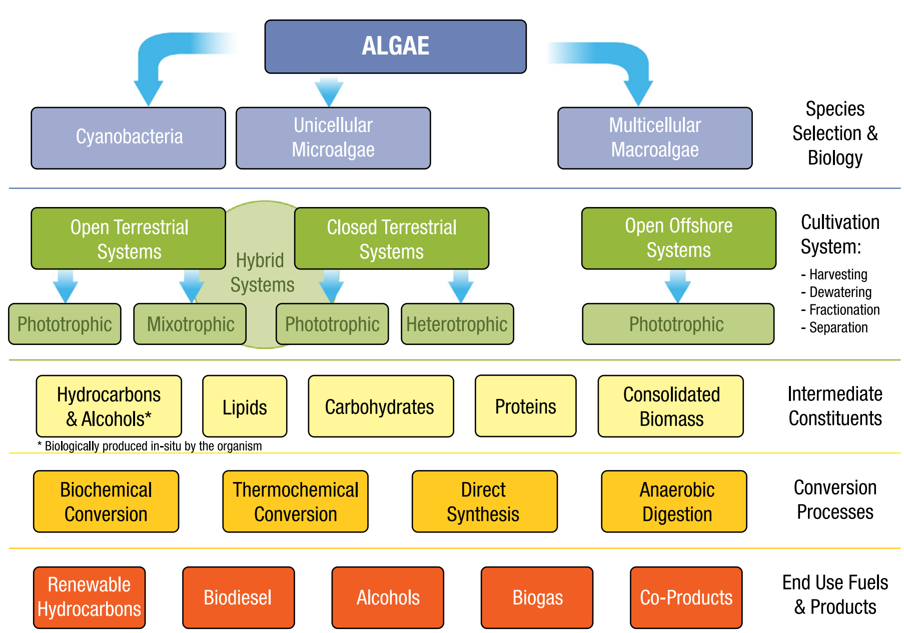

Fig. 1. Approaches and pathways of developing algae-based fuels and co-products.
Source: [1].

Table 1
Oil yields from various biomass sources and biofuels productivity.
Source: [6,17–19].

Crop	Oil yield (l/ha/yr)	Biofuel productivity (kg/ha/yr)	Land use (m^2/year/kg biodiesel)
Corn	172	152	66
Soybean	446	562	18
Sunflower	952	946	11
Rapeseed	1190	862	n.a.
Jatropha	1892	656	15
Oil palm	5950	4747	2
Microalgae (30% oil by wt.)	58,700	51,927	0.2
Microalgae (70% oil by wt.)	136,900	121,104	0.1

Note: 1 l (Liter) = 0.2643 gallons, 1 kg = 2.2 pounds, 1 ha = 2.47 acres.

Table 2
Global annual value of macroalgae products.
Source: [9].

Product	Value
Human food (Nori, aonori, kombu, wakame, etc.)	$5 billion
Algal hydrocolloids	
Agar (Food ingredient, pharmaceutical, biological/microbiological)	$132 million
Alginate (Textile printing, food additive, pharmaceutical, medical)	$213 million
Carrageenen (Food additive, pet food, toothpaste)	$240 million
Other uses of seaweeds	
Fertilizers and conditioners	$5 million
Animal feed	$5 million
Macroalgal biofuels	Negligible
Total	$5.5–6 billion

maximization might be among the major factors determining the final use of the algal feedstock and, further, the development of the algae-based fuel market in the long-term.

3. Economic, environmental, social and policy perspective on algae-based fuels

Algal biomass has several characteristics that make it competitive with other biofuels feedstocks for biofuels production.

3.1. Environmental advantages

Algae require 2 g of CO_2 for every g biomass generated [10]. Thus, algae assimilate CO_2 instead of releasing it, as is the case with the production of most feedstocks and crops. According to Hon-Nami [11] and Hirayama et al. [12], one ton of CO_2 can be converted into 60–70 gallons of algae-based ethanol. Therefore, algae have a huge potential to considerably contribute to GHG emission reductions right at the very first stage of the feedstock production. Therefore, algae-based fuel is said to be carbon-neutral, i.e., it releases the same amount of CO_2 upon fuel combustion that is assimilated by algae and necessary for its growth in the first place [13]. For this reason, algae-based fuels are said to be the most effective and sustainable response to climate change and the only renewable energy resource that has the capacity to meet the global demand for fuels in the long-term [14].

Moreover, the production of algae-based fuels can enhance positive external effects. Currently, the large corn ethanol plants are considered to be the major CO_2 emitters (19 pounds CO_2/bushel of corn) due to the fermentation during the ethanol production process. BioProcess Algae and Green Plains Renewable Energy created a white biotechnology and carbon remediation collaboration group to capture the CO_2 emissions from corn-based ethanol production and use it for algae-based fuel production. According to their estimations, a 100 million gallon corn ethanol plant emits enough CO_2 to produce 140,000 t of algae. Thus, negative effects of corn ethanol production can be mitigated with algae production and create an additional welfare value [15].

In the US, the corn ethanol capacity amounts to 14 billion gallons and represents 4.8 billion bushels of corn being processed; and it generates 43.2 million tons of CO_2. The recognition of the leveraging effects of algae has created a CO_2 trading mechanism on the biofuels market. Algenol (a research and development company) has estimated their CO_2 acquisition at $30/ton. Even with a lower CO_2 price of $25 (which would be similar to the Australian CO_2 trading price of $A 23/ton), the amount of traded CO_2 would be enough to produce 21 million tons of algae in the US. Assuming the lowest lipid content in algae of 30%, it would be enough to produce 1.6 billion gallons of renewable diesel or biodiesel [15].

In addition, algae production does not compete for water resources with the agricultural production. Algae can be grown with wastewater which indicates a high environmental sustainability of this feedstock (compare: [1]).

3.2. Economic advantages

Algae have a wide range of applicability and it can provide both fuels and co-products for other sectors. Three components can be extracted from the algal biomass: lipids, carbohydrates and proteins. Lipids and carbohydrates can be applied for fuel production (e.g., gasoline, biodiesel and jet fuel, renewable hydrocarbons, alcohols, biogas), while proteins can be used for other purposes (e.g., animal/fish feeds, fertilizers, industrial enzymes, bioplastics, surfactants) [1].

Two algae strains (*Chlorella vulgaris* and *Chlamydomonas perigranulata*) have a potential of producing 4000–6000 gallons ethanol/acre/year, with potential increases up to 10,000 gallons/acre/year provided technological developments occur (compare: [11,12]). Algae can produce between 10 and 100 times more oil per acre as compared with traditional crops (e.g., oil palm – one of the most oil-rich conventional biofuels feedstocks nowadays)[1] (compare: [16]), while the oil productivity of other feedstocks is even more limited (Table 1).

Another economic benefit of algae-based biofuel production is that the algae strains can grow in saltwater and harsh conditions (e.g., non-arable land). Thus, they neither compete with traditional crops for fresh water and quality soil nor with other biofuels feedstocks for land, water or fertilizers. The US Department of Energy (DOE) estimated that in order to completely replace traditional gasoline with algae-based fuel in the US, 15,000 square miles of land for its production would be necessary. This is an equivalent of only 0.42% of the total US area and less than 1/7th of the area used for corn plantation in 2000 [20,21]. If cultivation off-shore or near-shore is considered, algae production does not require land resources at all.

Algae-based fuels can also have technological advantages in terms of their distribution and marketing. They can be implemented as 'drop-in fuels', which means that they can be used as a supplement and mixed with gasoline, jet fuels and diesel. It can be refined and distributed by means of the same infrastructural equipment as is used for the traditional gasoline. Thus, algae-based fuel technology can be implemented without time delays,

[1] Such capacities have been confirmed only on the experimental scale and need a commercial scale validation.

additional infrastructural costs or any additional fuel cost increase at the pump, as is the case with other advanced biofuels, e.g., cellulosic ethanol.

Moreover, algae-based fuel has similar biochemical characteristics (energy density, number of carbon atoms per molecule) as traditional gasoline and, as recently proved by Solazyme [22] (an industrial biotechnology company), it can be used with factory-standard engines, without any modifications.

3.3. Social and policy advantages

Algae can be seen as a viable substitute for both the traditional oil market (diesel and gasoline) and biofuels (biodiesel and corn-based ethanol). It could create a new niche for leveraging negative effects of the current drought and the existing tradeoffs between food/feed and fuel production from the corn feedstock.

If applied to biodiesel and ethanol production on a large scale (with other advanced biofuels technologies, e.g., switchgrass, miscanthus, waste oil), algae-based fuels could mitigate negative effects of spiking crude oil prices (and subsequently gasoline prices) and further reduce the dependency on foreign oil imports. It would further foster R&D in other renewable energy fields and biofuels of the future.

Other than corn, sugar cane or other food-crops, algal feedstock is not impacted by food market price volatilities, which ensures higher price stability of the algae-based fuel for the consumers.

In addition to the positive welfare effects, the development and implementation of algae-based fuels can bring about social benefits. According to its most recent release, Algenol will create thousands of jobs in Southwest Florida with a start of a new commercial algae-based fuel production as early as of 2013. The company estimates the production costs of algae-based ethanol at the market price of a dollar per gallon [23]. If implemented on a large scale, algae-based fuels can become an important niche on the biofuels market and would help to alleviate negative effects of the recent gasoline price spikes.

4. Practical limitations to algae technology and prospective solutions

The positive aspects of algae-based fuel production in terms of the economic, environmental and social aspects have not been sufficient at present to produce algae on a large commercial scale. One of the main impediments has been the high production costs and thus low cost efficiency of the final algae-based fuels.

Algae biology and specific cultivation, harvesting and dewatering requirements, as well as the high costs of the conversion process, extraction and fractionation, fuel and co-product conversion, have limited the development of this technology for many years (compare: [1,24,25]). Currently, with the investments of private companies, the main production barriers have been overcome, and algae-based fuel is currently supplied to the US Navy and US Marines [22].

Still, the cost efficiency aspect is the main challenge to immediately implement the algae technology on a large commercial scale and at an acceptable consumer price of the algae-based fuel, to be affordable and competitive with traditional gasoline prices.

The price for the final algae-based fuel can vary, depending on the applied production technology (photobioreactors, open ponds or hybrid systems, which are all traditional ways of growing algae nowadays). An experimental study by Dimitrov [26] has found that algae oil produced with the GreenFuels photobioreactors could be competitive with gasoline only at the oil price of $800/barrel. In its report, US Department of Energy estimated the price of algae-based fuels produced on a large scale to be more than $8/gal (as compared to $4/gal for soybean-based fuel) [27]. Although, the cost estimations clearly vary among different studies, all evaluations conducted over a longer time period confirm a clear trend of a price decrease of algae-based fuels. According to Gallagher [13], over the past 30 years, the estimated price for algae-based oil (normalized to 2009 price values) has decreased from $6.09 in 1982 [28] to $2.41 in 1996 [29]. This shows technological developments and indicates promising prospects for affordable algae-based fuel production on a commercial scale that could be competitive with the traditional gasoline.

4.1. Economic solutions

Recent developments in the field along with industry investments by e.g., Solazyme (one of the biggest algae-based fuels producers) show that cost efficiency of algae can be improved by reducing intensive energy inputs [30]. This can also be achieved by using those algae strains that are characterized by very high lipid content, as well as by developing technological solutions that would allow one to lower energy intensity of harvesting and drying algae biomass. The production costs of algae are also determined by the nutrient supplies of nitrogen, phosphorous, iron and silicon [31] that need to be closely monitored to avoid impeded efficiency or algae overgrowth and the resulting toxicity and eutrophication of surface waters. Thus, the cost efficiency can also be increased on this level by implementing low energy appliances and technological solutions.

Another innovative solution to the high processing costs is the newly introduced '*direct-to-ethanol*'® process marketed by Algenol which produces ethanol from cyanobacteria without the harvesting and dewatering stage, which clearly reduces the final ethanol costs. In this process, cyanobacteria are placed in low-cost closed flexible plastic film photobioreactors (PBRs) and the direct-to-ethanol system first takes advantage of algae's ability to produce sugar (pyruvate) from CO_2 and saltwater via photosynthesis. It then secrets ethanol from the cell into the saltwater medium as the next step. As the solar radiation intensifies during the day, ethanol concentrations build up and the ethanol evaporates into the 'head space' inside the PBR. As the sun goes down, the evaporated ethanol and water condense into droplets, which run along the plastic walls and into the ethanol collection rails, where it is removed from the PBR (Fig. 2). The remaining water and ethanol are further separated. The 'direct-to-ethanol'® process allows for producing high-value ethanol from CO_2, water (also wastewater) and sunlight without competing with food/feed production for arable land or fresh water [32]. The goal of Algenol is to reach the cost of $1.50–$1.70/gal at the current productivity levels, while Joule Unlimited is seeking to offer algae-based ethanol for $1.00/gal.

A study by US DOE [1] estimated that the production costs of algae-based fuels will also considerably decrease with growing R&D investments and will reach a cost level viable for commercial production in the mid-term, e.g., 5–15 years (Fig. 3).

Another technology allowing for reducing costs and increasing efficiency of algae-based fuels has been introduced by Joule Unlimited and Algenol. It suggests '*milking algae*' instead of harvesting them. This approach would allow for increasing oil yields by 50–150% (yields per pound of CO_2) as compared to the traditional algae harvesting method [15]. OriginOil presented the patent-pending 'Live Extraction™' milking algae process which would allow for algae oil (stored behind a tough cell wall) to be produced continuously by stimulating the cells through specific electrical modulations. In this way, a single algae cell is not destroyed and can produce more oil during its lifetime with a lower amount of energy input as compared to the harvesting process.

When using the traditional algae harvesting method, OriginOil estimated potential algae-based fuel production costs at the level of $2.28/gal for gasoline or diesel using a blend of algae and waste

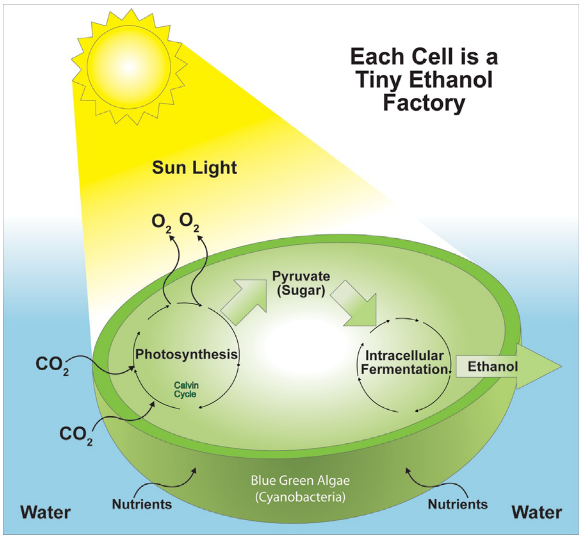

Fig. 2. Algae cell and 'direct-to-ethanol' process.
Source: [33].

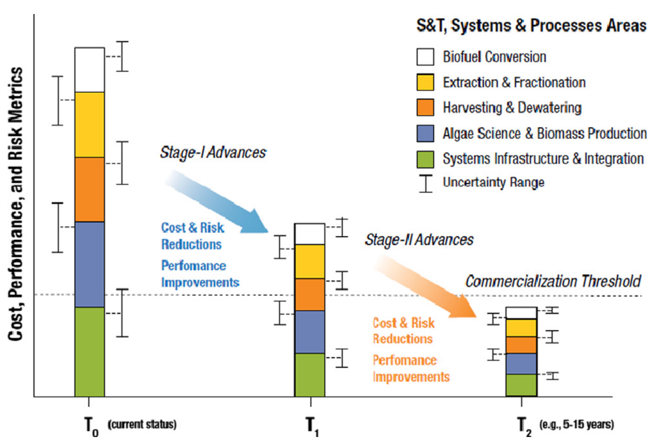

Fig. 3. Roadmap Timeframe Multi-Stage for R&D, commercialization and deployment of algae-based biofuels.
Source: [1].

feedstocks and the land area of at least 50 ha (124 acres). The cost would double up to $5.44/gal if pure algae feedstock is used [34].

While the industry purports the algal feedstock as a source of unlimited possibilities, scientists try to estimate biological limitations of the feedstock. In their study, Weyer et al. [35] calculated the optimistic scenario for algae-based fuel production based on realistic efficiencies of the feedstock and technologies. They found the theoretical maximum to be 38,000 gal/ac/year of unrefined oil, while the best case ranges from 4350 to 5700 gal/ac/year.

However, even biological limitations of the algae feedstock can be overcome with *genetic engineering* that could allow faster growth of algal biomass and/or higher lipid yields [36]. A study of Rodolfi et al. [37] showed that lipid accumulation in algae occurs during periods of environmental stress, e.g., growth under nutrient-deficient conditions. Increasing the activity of the enzyme responsible for the accumulation of lipid and fatty acids in microalgae via genetic engineering would allow for enhancing lipid production rates. The study showed that two microalgal strains (eustigmatophyte and nannochloropsis sp. F&M-M24) attained 60% lipid content after nitrogen starvation. Lipid productivity increased from 117 mg/l/day in nutrient sufficient conditions (with an average biomass productivity of 0.36 g/l/day and 32% lipid content) to 204 mg/l/day (with an average biomass productivity of 0.30 g/l/day and more than 60% final lipid content) in nitrogen-deprived conditions. In a two-phase cultivation process (a nutrient sufficient phase to produce the inoculum followed by a nitrogen deprived phase to boost lipid synthesis), the oil production could reach more than 90 kg/ha/day. In addition, the study found that the eustigmatophyte algae strain has the potential to produce 20 t of lipid per hectare annually in the Mediterranean climate and more than 30 t of lipid per hectare in sunny tropical areas.

Other authors point out the necessity of combining different production technologies to make them sustainable and more cost-efficient in the mid- and long-term. Subhadra and George [38] introduced an algae-based fuel production farm and shrimp culture integrated with wind energy sector. Also Trent [39] developed a project '*Offshore Membrane Enclosures for Growing Algae*' (OMEGA) that has the potential to be developed into the world's first marine photobioreactor. The OMEGA system is an off-shore network of floating photobioreactors for growing microalgae in a marine environment using municipal wastewater as the source of water and nutrients for algae, while waves provide the energy for mixing and sequestering CO_2. OMEGA does not compete for agricultural land and, because it uses municipal wastewater as the feedstock, it does not require freshwater or fertilizers (Fig. 4).

The objective of the project is to design, test and analyze PBRs to model a full-scale algae farm deployment and to arrive at a 35% system design that would function in actual marine environments. OMEGA addresses many relevant problems and clearly offers a competitive solution as compared to land-based algae cultivation systems in terms of economics, cooling, mixing, energy, water, and land use. However, it also has its limitations and unsolved problem regarding species control, harvesting, dewatering. It also faces several challenges associated with its offshore location (engineering, materials, permits) and the impact on marine ecosystem coastal area fishing, boating and ship traffic. A possible cost reduction of this system could be achieved by incorporating wind and solar facilities to produce other forms of energy in addition to algae-based fuels (compare: [39]).

4.2. Policy solutions

On the policy level, one of the effective ways to boost algae-based fuel production is establishing transparent policy frameworks and instruments, e.g., subsidies and mandates.

As of the end of 2012, no tax incentives exist for the production of algae-based fuels. The lack of subsidy instruments has not harmed the algae sector in the past, since the algae-based fuels have not been available on a commercial scale and the strong R&D support for the commercialization of algae-based fuels has just recently begun. The US Government expressed its support for algae-based fuels as the Senate Finance Committee approved a bill in August 2012 that would extend, for the first time in history, the cellulosic biofuel tax credit to include algae-based fuels [40]. Until the bill is in force, algae fuel research and investments will benefit mainly from private grants and collaborations with the major oil companies, such as ExxonMobil, Chevron, BP, as well as Dow Chemical.

When produced on the commercial scale, algae-based fuels would count for the 'advanced biofuels' mandate that was established by the Environmental Protection Agency (EPA) in 2007 with the Renewable Fuel Standard (RFS2) in the framework of the Energy Independence and Security Act (EISA). The mandatory RFS2 requires transportation fuels sold in the US to contain a minimum of 36 billion gallons of renewable fuels, including at least 21 billion gallons from advanced (non-corn ethanol), cellulosic biofuels and biomass-based diesel, by 2022 [1]. The 'advanced biofuel mandate' category is supposed to reach the level of 21 billion gallons by 2022 and

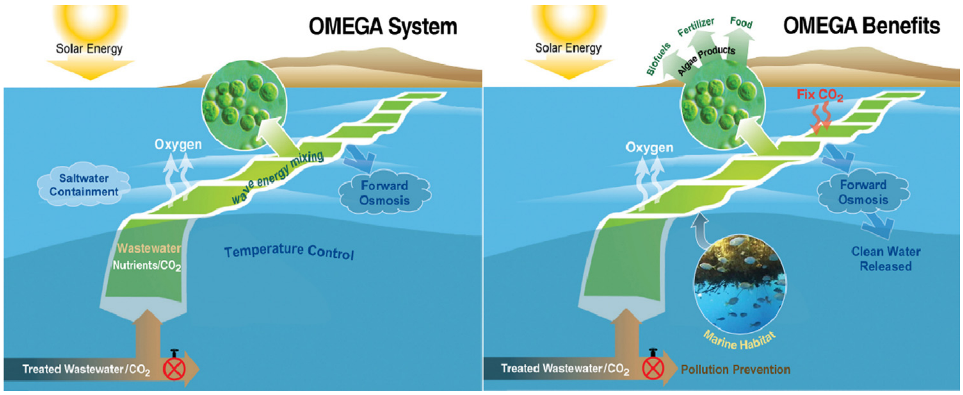

Fig. 4. OMEGA system (left) and OMEGA benefits (right).
Source: [39].

contribute by at least 50% to the GHG emission reductions as compared to the traditional fuel emission levels [41].

In the past decades, financial support for research and development on algal technology from the US Government has been provided in limited scope and with limited success. The algal technology is not new as such, but it took many years to reach the current point of the first commercial supplies for the US Navy and US Marines. Research on algae and its industrial potentials was initiated in 1950s [42,43], while algal biomass has been considered as a feedstock for biofuels production in the early 1970s during the oil embargo that resulted in high oil prices. In 1978, the United States Department of Energy launched the Aquatic Species Program to investigate potentials of algae for biofuels production, while several pilot cultivation plants have been established in California, Hawaii and New Mexico. The project was discontinued in 1996 based on a general conclusion about low cost-effectiveness of algae-based fuels as compared to the traditional gasoline [44,45]. In 2008, the Bioenergy Program for Advanced Biofuels launched under the Farm Bill 2008 has continuously supported farmers producing advanced biofuels feedstocks from 2008 to 2012. The bill provided $55 million in 2009 and 2010, $85 million in 2011 and $105 million in 2012 [46].

Over many years, pilot projects have been launched and conducted by several US universities, e.g., The University of Arizona, University of Illinois at Urbana-Champaign, University of California San Diego, University of Texas at Austin, University of Maine, University of Kansas, The College of William and Mary, Northern Illinois University, University of Texas at San Antonio, University of Georgia, Old Dominion University, Utah State University, New Mexico State University and Missouri University of Science and Technology.

However, the development of the algal technology and algae-based fuels was possible mostly due to private investments. Nowadays, Solazyme and Chevron, Shell and HR Biopetroleum, Global Green Solutions, Valcent Products and International Energy provide the market with algae-based fuels. Shell, Chevron, ExxonMobil and British Petroleum have invested around $1 billion in developing algae-based fuels due to their positive sustainability indexes and the prospects of large economies of scale [38]. In 2010, Solazyme delivered more than 21,000 gallons of algae-based diesel to the US Marines (Soladiesel) and jet fuel to the US Navy (Solajet). At the same time, Emerging-Markets estimated that algae-based fuel (also called 'green crude'), supplied by Solazyme and Sapphire Energy, will reach the level of 6 million gallons by 2025 [34].

Nowadays, the industrial attempts to commercialize algae-based fuels find a strong political support of the US Department of Energy. According to Lane [47], and assuming a conservative estimate of 13 g/m^3/day of algae growth, the US has the capacity to produce 5 billion gallons of algae-based fuel per year, provided a sufficient amount of the available resources: sunlight, water/wastewater, nutrients, sites and CO_2. However, current DOE Biomass Program seeks to achieve even a higher efficiency of algae growth (35 g/m^3/day), which would considerably increase the total production potential in the US. In response to the growing industry interest and investments in algae-based fuels, the DOE expressed the possibility of targeting a 40% reduction in operating costs from 2013 on [47].

In March 2012, the White House announced up to $35 million over three years to support research and development in advanced biofuels, bioenergy and high-value biobased products. The projects will be funded through the Biomass Research and Development Initiative (BRDI) – a joint program of the U.S. Department of Agriculture and the US Department of Energy [48].

According to the recent statement of the US National Research Council, 'Biofuels made from algae, …, cannot be made now on a large scale without using unsustainable amounts of energy, water and fertilizer' [49]. It is important to realize that at the current development stage of the algae technology, algae-based fuels can be used solely as drop-in biofuels. They bear a high potential for supplementing traditional fuels to a certain degree; however, this process requires several years of intensive research and development.

The enumerated examples show a strong support of the industry sector and the US Government for algae fuel technology in recent years and constitute an investment-friendly environment for the further R&D in the field.

5. Conclusions

In the past decade, algae have been discussed as a promising feedstock for biofuels production. However, missing technological infrastructure, low economies of scale and low cost-effectiveness of the algae-based fuels were the main impeding factors for a rapid development of this technology. Due to permanent attempts of science and industry to minimize production costs, algae have proven to be a superior feedstock for biofuel production as compared to other biofuels feedstocks in terms of its high environmental index and high energy efficiency of the final fuel. Algae do not compete with other feedstocks for natural resources and further, they do not impact food prices as is the case, for instance, with corn-based biofuels (compare: [50–53]).

The main impediments for the commercialization of algae-based fuels have been high production costs. However, recent developments seek to reduce the final at-the-pump costs down to $1.00–$1.70/gal at the current productivity levels.

Several technological approaches have been introduced, mostly by the industry sector to accelerate research and development of the algae fuel technology. Most of them emphasize the necessity of

reducing energy inputs in the production process. Among the new technologies are: '*milking algae*' (that allows for continuous deriving of algal oil instead of their one-time harvesting and processing), *genetic engineering* (for increasing algae growth and lipid production by algal cells), '*direct-to-ethanol*'® process (which produces ethanol from cyanobacteria without the harvesting and dewatering stage) and *combined off-shore systems*, e.g., Offshore Membrane Enclosures for Growing Algae (that could incorporate algae production, in addition to wind and solar facilities).

Several steps have been taken by the US Government in recent years to support algae-based fuel production, starting with a tax credit incentive and the $35 million project on advanced biofuels, bioenergy and high-value biobased products sponsored by USDA and US DOE.

Due to optimistic experiences of the industry sector with the development and production of the algae technology in recent years, the prospects for this feedstock to become a feedstock of the future are promising. However, further research and developments are necessary to make algae-based fuels an affordable product.

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